Levels in ^{223}Th populated by α decay of ^{227}U

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Levels in ^{223}Th populated by the α decay of ^{227}U were investigated using α-γ decay spectroscopy. The ^{227}U isotope was produced in the fusion-evaporation reaction ^{22}Ne + ^{208}Pb at the velocity filter separator for heavy-ion reaction products at Gesellschaft für Schwerionenforschung in Darmstadt (Germany). Several new excited levels and γ transitions were identified in ^{223}Th. An improved α-decay scheme of ^{227}U was suggested. The experimental α-decay energy spectrum of ^{227}U was compared with the Monte Carlo simulation performed using the toolkit GEANT4.

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I. INTRODUCTION

The first study of excited levels in ^{223}Th was reported more than 20 years ago [1]. In that work, ^{223}Th was investigated in beam by applying the reaction ^{208}Pb + ^{18}O. The main part of the measurements was performed at the Max-Planck (MP) tandem accelerator of the Max-Planck Institut für Kernphysik in Heidelberg, Germany. The ground state of ^{223}Th was assigned as $5/2^+$ based on theoretical predictions and the similarity with the isotonic nucleus ^{221}Ra.

Shortly after that experiment, an out-of-beam study of excited levels in ^{223}Th was performed at the cyclotron facility at Louvain-la-Neuve, Belgium [2]. In that study, the compound nucleus ^{230}U was synthesized in the reaction ^{22}Ne + ^{208}Pb, and ^{223}Th was produced by the α decay of ^{227}U (produced in the 3n evaporation channel of the considered reaction). To avoid admixtures of isotopes other than ^{227}U-^{223}Th, the studied α-decay energy range of ^{227}U was restricted to 6.76–6.92 MeV. This limitation prevented the observation of higher-energy levels and transitions in ^{223}Th.

While higher-energy levels can be well studied by in-beam methods, lower-energy ones can be well investigated by the α-decay spectroscopy. These different approaches resulted in different levels observed in ^{223}Th in previous studies [1,2]. In this work we present the results of the measurement aimed at the study of the α decay of ^{227}U and excited levels in its daughter nucleus ^{223}Th investigated by the α-γ decay spectroscopic methods.

II. EXPERIMENT

In our experiment, the ^{227}U nuclei were produced in the fusion-evaporation reactions ^{22}Ne + ^{208}Pb at Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany. A beam with an average intensity of ~90 pnA (1 pnA = 6.242×10^9 particles/s) was delivered by the Universal Linear Accelerator (UNILAC). The beam energy was 104 MeV in front of the target, resulting in compound nuclei ^{230}U with an excitation energy of 32 MeV (considering the production at 2/3 of the target thickness). Eight targets were mounted on a wheel rotating synchronously to the beam macrostructure (5.5-ms-long pulses at 5-Hz repetition frequency most of the irradiation time). Targets were prepared from a compound ^{208}PbS material and had an average thickness of ~420 μg/cm^2, which corresponds to a contribution of ~360 μg/cm^2 of ^{208}Pb. They were evaporated on a 40-μg/cm^2 carbon backing and covered with another 10-μg/cm^2 carbon layer to increase the emissivity of the target and to avoid sputtering of the target material.

Evaporation residues (ERs) were separated from projectiles and products from reactions other than complete fusion by the velocity filter separator for heavy-ion reaction products (SHIP) [3] and transmitted with a 5% efficiency [4] into a focal-plane detector system. There they were implanted into a 300-μm-thick 16-strip position-sensitive silicon detector (PSSD). The implantation depth of ERs in the PSSD, calculated using the software SRIM [5], was ~1.6 μm. The energy resolution and the geometric detection efficiency of the PSSD for a 7-MeV α particle were ~25 keV (FWHM) and 52 %, respectively. For the energy calibration of the PSSD we used the α peaks from isotopes also produced in the studied reaction ^{22}Ne + ^{208}Pb: 5304.33(7) (^{210}Po), 6278.2(7) (^{211}Bi), 6478(3) (^{225}Th), 7000(10) (^{224}Th), 7170(10) (^{224}Th), 7980(2) (^{222}Th), 8088(8) (^{213}Rn), and 11660(10) keV (^{212}Po^m).

Particles escaping from the PSSD to the backward hemisphere were detected by the system of six silicon detectors (the so-called box) placed upstream, with the beam forming a box around the PSSD. The geometric efficiency of the box system was 80% of 2π [6] and the energy resolution was ~90 keV (FWHM) for the α particles escaping from the PSSD.

A four-crystal germanium clover detector was placed close behind the PSSD to detect γ rays. The crystals had a diameter of 50–55 mm and a length of 70 mm and were shaped to form a block of $102 \times 102 \times 70$ mm^3. The energy resolution (FWHM) and the detection efficiency of the clover detector were 1.9 keV and ~10 % [7], respectively, at $E_\gamma \approx 80$ keV.

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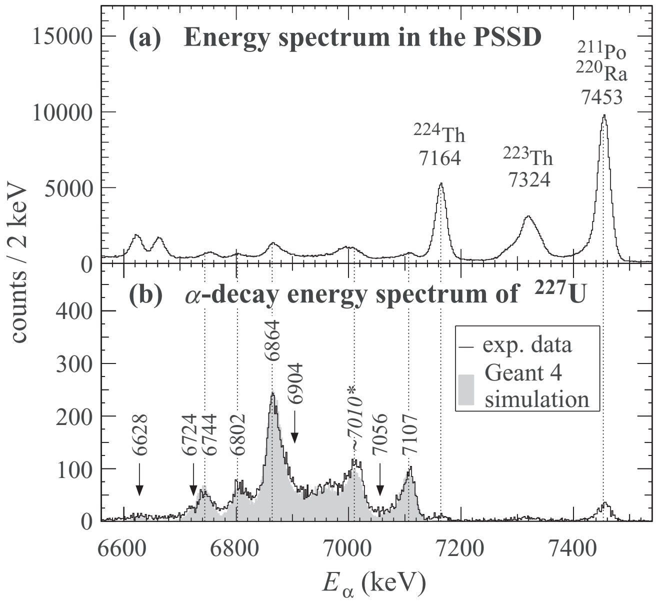

FIG. 1. (a) Part of the energy spectrum measured in the PSSD in the reaction ^{22}Ne + ^{208}Pb at a beam energy of 104 MeV. (b) Events from panel (a) detected as $\alpha 1$ decays in the $\alpha 1(^{227}\mathrm{U})$-$\alpha 2(^{223}\mathrm{Th})$-$\alpha 3(^{219}\mathrm{Ra})$ correlation search. The search conditions were optimized for $\alpha 1$ decays of ^{227}U and suppression of other decays. The peak at ∼7010 keV marked by an asterisk is a so-called artificial peak created by the energy summing of α particles and conversion electrons and does not correspond to an α line of ^{227}U (see the decay scheme of ^{227}U in Fig. 3). The experimental data (black solid line) are compared with the result of the Monte Carlo simulation performed using GEANT4 [10] (shaded area).

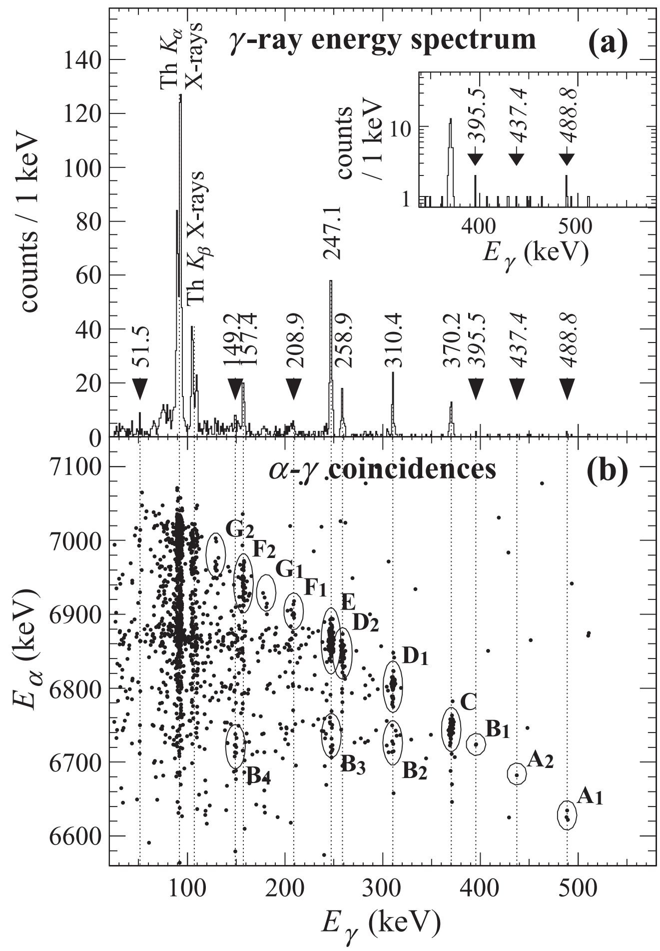

FIG. 2. (a) Energy spectrum of γ rays detected within a 5-μs coincidence time after the $\alpha 1$ decays of ^{227}U [from the $\alpha 1$-$\alpha 2$-$\alpha 3$ correlation search; see Fig. 1(b)]. The inset shows the higher-energy part of the spectrum where the number of counts are given in logarithmic scale to better present the weak transitions at 395.5, 437.4, and 488.8 keV (marked by italic font). Their positions were deduced based on the α-γ analysis [see panel (b) and the text for details]. (b) α-γ coincidence spectrum showing pairs of α particles (vertical axis) and γ rays from panel (a) (horizontal axis) detected within a coincident time of 5 μs.

Nuclei were identified using the position and time correlation method of subsequent α-decay signals. (For more details on the correlation method, see Ref. [8].) The maximum accepted position differences between these signals were set to be ±0.4 mm. Calculated intensities of the γ lines and x rays were corrected for the detection efficiency [7]. The α-decay hindrance factors were determined as the ratio of the experimental and expected half-lives. The latter were calculated using the approach introduced by Poenaru *et al.* [9].

III. RESULTS AND DISCUSSION

A part of the energy spectrum measured in the PSSD is shown in Fig. 1(a). The dominant α peaks in the spectrum correspond to decays of ^{224,223}Th produced in the αxn evaporation channels and their daughter products.

To extract the information on the decays of ^{227}U only, and to suppress decays of other isotopes, we applied several conditions in our analysis. We searched for the correlated $\alpha 1(^{227}\mathrm{U})$-$\alpha 2(^{223}\mathrm{Th})$-$\alpha 3(^{219}\mathrm{Ra})$ decay chains. Time windows of 90 ms $< \Delta t(\alpha 1$–$\alpha 2) <$ 3 s and 0.5 ms $< \Delta t(\alpha 2$–$\alpha 3) <$ 50 ms were selected to cover most of the true correlation chains and to eliminate the shorter-lived activities. These activities contributing to background $\alpha 2$- and $\alpha 3$-decay signals are, for example, isotopes of ^{220}Ra (from the ^{228}U decay chain, $T_{1/2}(^{220}\mathrm{Ra}) = 18(2)$ ms [11]) and ^{215}At (from the ^{227}Pa decay chain, $T_{1/2}(^{215}\mathrm{At}) = 0.10(2)$ ms [11]), respectively. We searched for the $\alpha 2$ and $\alpha 3$ decays in both PSSD and PSSD + box system. However, considering the better energy resolution of the PSSD itself compared to the PSSD + box system, we only accepted signals in the PSSD as candidates for the $\alpha 1$ decay (^{227}U). Applying given conditions on decays in Fig. 1(a), we obtained the $\alpha 1$ spectrum shown in Fig. 1(b). The background from the dominant peaks from Fig. 1(a) is considerably reduced and predominantly the decays of ^{227}U are present in Fig. 1(b).

In total, ∼50 000 evaporation residues of ^{227}U were implanted into the PSSD. The cross section for the production of ^{227}U at the beam energy of 104 MeV was evaluated to be 11(2) μb.

The γ rays detected in coincidence with $\alpha 1$ decays from the $\alpha 1$-$\alpha 2$-$\alpha 3$ correlation search [Fig. 1(b)] are shown in Fig. 2. Figure 2(a) shows the γ-ray energy spectrum and panel (b)

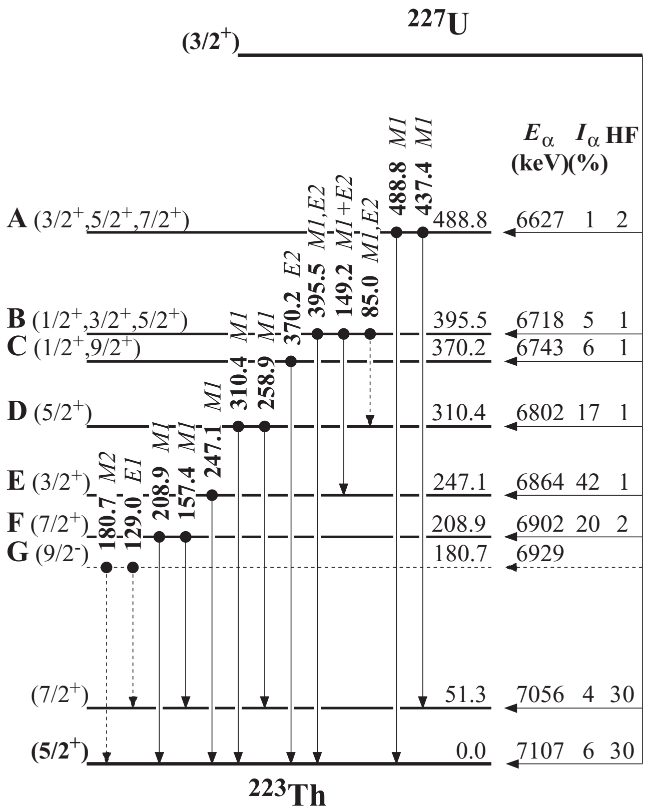

FIG. 3. Suggested α-decay scheme of ^{227}U. Uncertainties of all values are given in the text and in Tables I and II. The lettering of the levels on the left side corresponds to the lettering of the α-γ groups in Fig. 2(b). Spins and parities of the levels and multipolarities of the transitions are tentative.

presents a two-dimensional plot of coincident α-γ events. In agreement with the observation at Louvain-la-Neuve [2], we detected γ lines at 157, 209, 247, 259, and 310 keV from ^{223}Th (marked as F_2, F_1, E, D_2, and D_1, respectively, in Fig. 2(b). Note that the same letters represent the transitions (or cascades of transitions) stemming from the same levels. Lettering corresponds to that in the decay scheme in Fig. 3). Besides these lines, we also registered several new γ transitions, which we attributed to ^{223}Th as well (see later in the text).

A. α-γ coincidence analysis

Following the α-decay scheme of ^{227}U published previously [2], the 310- and 247-keV γ transitions populate directly the ground state of ^{223}Th. The sums of the Q_α values of the α transitions populating the 310- and 247-keV levels and the energies of corresponding internal transitions are 7234(4) and 7234(3) keV, respectively. This value represents the Q_α value of the transition from the ground state of ^{227}U to the ground state of ^{223}Th.

1. Level at 370 keV

For the strong α-γ coincidence group at $E_\gamma = 370.2(3)$ keV and $E_\alpha = 6744(4)$ keV [marked as C in Fig. 2(b)], we get $Q_\alpha + E_\gamma = 7235(4)$ keV. This value agrees with the Q_α value of the α decay to the ground state of ^{223}Th (evaluated as 7234(3) keV). Therefore, we assume the existence of a level at 370.2(3) keV in ^{223}Th, which decays to the ground state by an internal transition.

2. Levels at 489 and 396 keV

For two weak α-γ coincidence groups at $E_\alpha = 6628(7)$ keV, $E_\gamma = 488.8(6)$ keV [three events, A_1 in Fig. 2(b)] and $E_\alpha = 6724(8)$ keV, $E_\gamma = 395.5(7)$ keV [two events, B_1 in Fig. 2(b)], their values of $Q_\alpha + E_\gamma$ are 7236(7) and 7240(9) keV, respectively. These values correspond to the Q_α value of the transition between the ground states of ^{227}U and ^{223}Th. Thus, we suggest levels at 488.8(6) and 395.5(7) keV in ^{223}Th populated by the α decay of ^{227}U and decaying directly to the ground state.

One α-γ coincidence event was detected with $E_\alpha = 6684(11)$ keV and $E_\gamma = 437.4(1.0)$ keV [A_2 in Fig. 2(b)]. The γ-ray energy in this case is lower than the energy of the 488.8(6)-keV transition by 51.4 keV, which corresponds to the energy of the first excited $7/2^+$ level of the $5/2^+$ ground-state rotational band in ^{223}Th reported in the in-beam studies ($E^*_{(7/2^+)} = 51.3$ keV [1]). Therefore, we suggest a 437.4(1.0)-keV transition connecting the 488.8(6)- and 51.3-keV levels in ^{223}Th. The $Q_\alpha + E_\gamma$ values of both decays [7236(7) keV for the α decay in coincidence with the 488.8(6)-keV γ transition and 7241(12) keV for the α decay in coincidence with the 437.4(1.0)-keV γ transition] are equal within the error bars. This agreement supports our placement of these transitions into the decay scheme (Fig. 3), as the 51.3-keV transition is highly converted and thus its energy is often summed with the α-decay energy. Note that the weak 51.5(4)-keV γ line was also observed in our experiment (see Fig. 2).

The α decay with $E_\alpha = 6724(8)$ keV populating the 395.5(7)-keV level was observed in coincidence with several γ lines. Their energies are 395.5(7), 310.4(3), 247.1(3), and 149.2(4) keV [B_1, B_2, B_3, and B_4, respectively, in Fig. 2(b)]. From these coincidences we can deduce three possible decay paths of the 395.5(7)-keV level. The first one is the de-excitation through the single 395.5(7)-keV transition. The second one is the de-excitation through the cascade of the 247.1(3)- and 149.2(4)-keV transitions, as the sum of their energies [396.3(5) keV] is consistent with the level energy. The third possibility is the cascade of the 310.4(3)- and 85.1(8)-keV transitions. As the 85-keV transition was not observed in the γ-ray energy spectrum, we suppose a high internal conversion coefficient α_{tot} and exclude an $E1$ character. We sketched this transition by the dashed line in the suggested decay scheme in Fig. 3.

3. 180- and 129-keV transitions

We detected two weak groups of α-γ coincidences with $E_\gamma = 181$ and 129 keV [G1 and G2, respectively, in Fig. 2(b)]. They may arise from the decay of the 180-keV $9/2^-$ level in ^{223}Th observed in the in-beam measurements [1]. In that work, the first $7/2^+$ rotational level of the ground-state rotational band was populated, besides other decay paths, by the 129.3-keV transition from the $9/2^-$ level at 180 keV. Unlike the in-beam measurements, where only the 129.3-keV

TABLE I. The α-decay properties of ^{227}U extracted from our data. The α-decay energies, intensities, corresponding energies of excited levels populated in ^{223}Th, and hindrance factors are shown. The last two columns show α-decay energies and intensities taken from the experiment at Louvain-la-Neuve [2].

E_α (keV)	I_α (%)	E_{level} (keV)	hindrance factor	$E_{\alpha,\text{lit}}$ (keV) [2]	$I_{\alpha,\text{lit}}$ (%) [2]
6627(7)	1(1)	488.8(6)	2(1)		
6718(8)	5(1)	395.5(7)	1(1)		
6743(4)	6(1)	370.2(3)	1(1)		
6802(4)	17(3)	310.4(3)	1(1)	6740(50)	16(4)
6864(3)	42(7)	247.1(3)	1(1)	6860(30)	50(6)
6902(5)	20(4)	208.9(5)	2(1)	6900(60)	14(3)
7056(3)	4(4)	51.5(4)	30^{+200}_{-10}		10(6)
7107(3)	6(4)	0.0	30^{+70}_{-10}		10(6)

transition was detected from the 180-keV level, we registered both transitions (with 181 and 129 keV) with similar statistics. Although the 181-keV level might be populated by the 6929-keV α transition, this α decay should be rather hindered due to a change of parity (and spin) between the initial and final state. Thus, we sketched these transitions and the 181-keV level in the decay scheme by dashed lines (see Fig. 3) and do not include them in GEANT4 simulation (see Sec. III C).

B. Characters of the transitions

Evaluated hindrance factors for the observed new α transitions of ^{227}U are all below 10 (see the decay scheme in Fig. 3 and Table I). For such values of hindrance factors no change in parity between the connected states is expected [12]. As the initial α-decaying state in ^{227}U has positive parity, we also deduce positive parities for the observed levels populated in ^{223}Th.

TABLE II. List of γ rays attributed to ^{223}Th. Energies and relative intensities of γ lines extracted from our data are compared to those from literature (in last two columns [2]). Tentative multipolarities are also shown. The 85-keV γ line was not observed directly, but was deduced from the α-γ analysis. Intensities are corrected for the γ-ray detection efficiency [7] and are relative to the strongest 247-keV transition.

E_γ (keV)	I_γ (%)	Multipolarity	$E_{\gamma,\text{lit}}$ (keV) [2]	$I_{\gamma,\text{lit}}$ (%) [2]
488.8(7)	4(2)	$M1$		
437.4(1.0)	1^{+2}_{-1}	$M1$		
395.5(7)	2^{+3}_{-1}	$M1,E2$		
149.2(4)	4(1)	$M1+E2$		
85.0(8)	<1	$M1,E2$		
370.2(3)	32(10)	$E2$		
310.4(3)	28(8)	$M1$	310	18(6)
258.9(3)	21(6)	$M1$	259	15(6)
247.1(3)	100	$M1$	247	100(13)
208.9(5)	4(2)	$M1$	209	14(5)
157.4(3)	17(4)	$M1$	158	14(5)
51.5(4)	5(3)	$M1$	51.3(5) [1]	

1. 489- and 437-keV transitions

We observed three α1-γ coincidences with $E_\gamma = 488.8(6)$ keV and $E_\alpha = 6628(7)$ keV [A_1 in Fig. 2(b)] and four α1-(K x-rays) coincidences in the same α-decay energy window. The x rays have their origin in the decay of the level through an internal transition, which is partially converted. Considering relative intensities of γ transitions and K x rays, corrected for a detection efficiency [7], we can calculate internal conversion coefficients of the transitions. The evaluated lower limit for the experimental α_K for the 489-keV transition is 0.5(4). We can only evaluate the limit of α_K because part of the α decays populating excited levels is registered with higher energies due to the energy summing with conversion electrons. Theoretical values for α_K for the 489-keV transition of different multipolarities are 0.01 ($E1$), 0.03 ($E2$), 0.2 ($E3$), 0.2 ($M1$), 0.6 ($M2$), and 1.5 ($M3$) [13]. We exclude the $E1$ and $E2$ multipolarities due to too low theoretical α_K and exclude $M3$ and $E3$ multipolarities due to too long expected half-lives [14] (tens of microseconds for the $E3$ and milliseconds for the $M3$ character).

The $M2$ transition requires the parity change between the initial and final states. The ground state of ^{223}Th has a positive parity, and thus the 489-keV level should have a negative parity. As we excluded negative parities of the observed exited levels in ^{223}Th based on α-decay hindrance factors (see the beginning of Sec. III B), we also exclude the $M2$ character for the 489-keV transition. $M1$ is then the most probable character for this transition, suggesting the tentative spin and parity of $3/2^+$, $5/2^+$, or $7/2^+$ for the 489-keV level. The deduced tentative character for the 437-keV transition between the 489- and 51-keV levels is then $M1$ as well.

2. 149-, 396-, and 85-keV transitions

Considering a cascade of the (149 + 247) keV transitions stemming from the 396-keV level in ^{223}Th: We observed a group of 8 events [$E_\gamma = 149$ keV, B_4 in Fig. 2(b)] and 13 events [$E_\gamma = 247$ keV, B_3 in Fig. 2(b)] attributed to the considered cascade. As the character of the 247-keV line is known from the previous study [2], we evaluate the number of expected cascades to be more than 450. The calculated α_K for the 149-keV line is then ∼5.

Compared to the theoretical values for different multipolarities [13], the assumed character for the 149-keV transition is $M1$ or $E2$, or a mix of them. Then, the spin and parity of the 396-keV level is $1/2^+$, $3/2^+$, or $5/2^+$. This spin and parity assignment would suggest $M1$ or $E2$ characters for both the 396- and unobserved 85-keV transitions.

A similar assumption [as for the (149 + 247)-keV cascade] can also be made for the (85 + 310)-keV cascade. We observed 5 events [group B_2 in Fig. 2(b)] attributed to the 310-keV transition from the considered cascade. The character of the 310-keV transition is known from the previous study [2], and thus we expect more than 150 cascade transitions of 85 + 310 keV. As we do not see any clear peak at 85 keV in the γ-ray energy spectrum [Fig. 2(a)], the total internal conversion coefficient of the 85-keV transition is greater or approximately equal to 10 excluding the $E1$ character for this transition.

3. 370-keV transition

The multipolarity estimation for the 370-keV transition is less straightforward. In the α-decay energy window from 6710 to 6760 keV, where we observed α-γ coincidences from the decay to the 370-keV level [C in Fig. 2(b)], we also observed α-γ coincidences with several other γ lines at 396, 310, 247, and 149 keV. The number of K x rays detected in the same α-decay energy range is 34. We get less than 19 K x rays of the 370-keV transition after the subtraction of expected contributions to K x rays of other transitions. As the number of observed α-$\gamma(E_\gamma = 370$ keV) coincidences [C in Fig. 2(b)] is 36, the α_K for the 370-keV transition is then less than 0.4(1). Theoretical values for different multipolarities for the 370-keV transition are 0.02 ($E1$), 0.09 ($E2$), 0.5 ($E3$), 0.5 ($M1$), 1.5 ($M2$), and 4.0 ($M3$). The $E1$ transition would require different parities between the initial and final state, indicating negative parity of the 370-keV level (as the ground state of ^{223}Th has positive parity). However, we excluded negative parities for the observed levels in ^{223}Th populated by the α decay of ^{227}U based on the α-decay hindrance factors. Thus, we conclude that the tentative character of the 370-keV transition is $E2$ (or $M1 + E2$) and the spin and parity of the 370-keV level is $1/2^+$.

C. GEANT4 simulation

Based on our observations, we suggest an enhanced α-decay scheme of ^{227}U-^{223}Th (see Fig. 3). The information on α-decay energies and intensities of ^{227}U and energies of corresponding excited levels in ^{223}Th are summarized in Table I. In order to test the suggested decay scheme, we performed Monte Carlo simulation of the α decay of ^{227}U and subsequent de-excitation processes (conversion electron, x-ray, and/or Auger electron emission) in ^{223}Th using the toolkit GEANT4 [10]. The comparison between the experimental data and the result of the GEANT4 simulation is shown in Fig. 1(b). In the simulation, we used the energies and relative intensities of the α and γ transitions from Table I.

The relative intensities for the first six α decays in Table I were extracted from the α-γ decay data. The relative intensities for the last two decays were determined from the best agreement between the experimental and simulated α-decay energy spectra [see Fig. 1(b)]. The α-decay energy spectrum of ^{227}U is influenced by the summing of α-particle and conversion-electron energies. The summing effect caused a peak at ~7010 keV to appear in the spectrum, though ^{227}U does not emit α particles with this energy. The summing effect also hampered the estimation of relative intensities of the α transitions populating the ground state and its first rotational level at 51.3 keV in ^{223}Th. That is because the α-decay energy fully summed with the conversion-electron energy from the 51.3-keV level results in the same energy signal as for the ground-state to ground-state transition.

IV. SUMMARY

In this work we present the results of the α-γ decay study of ^{227}U-^{223}Th. The ^{227}U isotopes were produced in fusion-evaporation reactions at SHIP in GSI, Darmstadt. Excited levels in ^{223}Th were populated by the α decay of ^{227}U.

We improved the known α-decay data for ^{227}U and observed new levels in ^{223}Th (at 370.2(3), 395.5(7), and 488.8(6) keV) and several new γ transitions. Fair agreement was achieved between the experimental α-decay energy spectrum of ^{227}U and the result of the Monte Carlo simulation performed by GEANT4.

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[1] M. Dahlinger, E. Kankeleit, D. Habs, D. Schwalm, B. Schwartz, R. S. Simon, J. D. Burrows, and P. A. Butler, Nucl. Phys. A **484**, 337 (1988).

[2] T. H. Hoare, P. A. Butler, G. D. Jones, M. Loiselet, O. Naviliat-Cuncic, J. Vervier, M. Dahlinger, A. M. Y. El-Lawindy, R. Wadsworth, and D. L. Watson, J. Phys. G: Nucl. Part. Phys. **17**, 145 (1991).

[3] G. Münzenberg, W. Faust, S. Hofmann, P. Armbruster, K. Güttner, and H. Ewald, Nucl. Instr. Meth. **161**, 65 (1979).

[4] SHIPTRAP Collaboration, M. Mazzocco, D. Ackermann, M. Block, H. Geissel, F. Herfurth, F. P. Heßberger, S. Hofmann, N. Iwasa, K. Nishio, W. R. Plaß, C. Scheidenberger, H. Weick, M. Winkler *et al.*, Nucl. Instr. Meth. B **266**, 3467 (2008).

[5] J. F. Ziegler, J. P. Biersack, and M. D. Ziegler, SRIM-2013, The Stopping and Range of Ions in Matter (2013), http://www.srim.org/.

[6] A. N. Andreyev, D. Ackermann, F. P. Heßberger, S. Hofmann, M. Huyse, G. Münzenberg, R. D. Page, K. Van de Vel, and P. Van Duppen, Nucl. Instr. Meth. A **533**, 409 (2004).

[7] F. P. Heßberger, S. Antalic, B. Sulignano, D. Ackermann, S. Heinz, S. Hofmann, B. Kindler, J. Khuyagbaatar, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, A. G. Popeko, Š. Šáro, B. Streicher, J. Uusitalo, M. Venhart, and A. V. Yeremin, Eur. Phys. J. A **43**, 55 (2010).

[8] S. Hofmann, W. Faust, G. Münzenberg, W. Reisdorf, P. Armbruster, K. Güttner, and H. Ewald, Z. Phys. A **291**, 53 (1979).

[9] D. N. Poenaru, I.-H. Plonski, and W. Greiner, Phys. Rev. C **74**, 014312 (2006).

[10] S. Agostinelli *et al.*, Nucl. Instr. Meth. A **506**, 250 (2003), http://geant4.cern.ch/.

[11] R. B. Firestone and L. P. Ekström, database version 2.1, (2004) http://ie.lbl.gov/toi/perchart.htm.

[12] G. T. Seaborg and W. D. Loveland, *The Elements beyond Uranium* (John Wiley and Sons, New York, 1990).

[13] T. Kibédi, T. W. Burrows, M. B. Trzhaskovskaya, P. M. Davidson, and C. W. Nestor, Jr., Nucl. Instr. Meth. A **589**, 202 (2008).

[14] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).